Northeastern University

CS 6410: Compilers

Fall 2019

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Thank you to UW faculty Hal Perkins. Today lecture notes are a modified version of his lecture notes.

Credits For Course Material

- Big thank you to UW CSE faculty member, Hal Perkins
- Some direct ancestors of this course:
  - UW CSE 401 (Chambers, Snyder, Notkin, Perkins, Ringenburg, Henry, ...)
  - UW CSE PMP 582/501 (Perkins)
  - Cornell CS 412-3 (Teitelbaum, Perkins)
  - Rice CS 412 (Cooper, Kennedy, Torczon)
  - Many books (Appel; Cooper/Torczon; Aho, [[Lam,] Sethi,] Ullman [Dragon Book], Fischer, [Cytron ,] LeBlanc; Muchnick, ...)

Administrivia

- **My office hours:**
  - On Mondays from 10:30-12pm in 401 Terry Ave, 142 classroom
- **Quizzes:**
  - Nicely done with Quiz 2
  - Quiz 3 available until tomorrow (Wednesday at 12 noon)
- **Homework:**
  - Second homework posted – due on Sat, Oct 19
  - Fourth homework posted yesterday - due on Sat, Nov 2
- **Project setup:**
  - First part of the project???
  - Second part posted yesterday – due on Saturday, Nov 9

Administrivia

- Lecture next week – on Wednesday, October 23 from 10:30-1:30pm in 401 Terry, classroom 143

Agenda

- Review - LR Parsing
  - LR(0), SLR, LR(1), LALR(1)
  - FIRST, FOLLOW, and nullable
- Top-down parsing
- Static semantics
- Attribute grammars
- Symbol tables
- Types & type checking

Reading:

- Cooper & Torczon – chapter 3 and 5
- The Dragon book, chapters 4 and 6.1, 6.2

Review: Syntactic Analysis / Parsing

- Goal: Convert token stream to an abstract syntax tree
- Abstract syntax tree (AST):
    - Captures the structural features of the program
    - Primary data structure for next phases of compilation

Review: Common Parsing Orderings

- Top-down
  - Start with the root
  - Traverse the parse tree depth-first, left-to-right (leftmost derivation)
  - LL(k), recursive-descent
- Bottom-up
  - Start at leaves and build up to the root
    - Effectively a rightmost derivation in reverse(!)
  - LR(k) and subsets (LALR(k), SLR(k), etc.)

Review: Context-Free Grammars

- Formally, a *grammar G* is a tuple $<N,\Sigma,P,S>$ where
  - N is a finite set of *non-terminal* symbols
  - Σ is a finite set of *terminal* symbols (alphabet)
  - P is a finite set of *productions*
    - A subset of $N \times (N \cup \Sigma)^*$
  - S is the *start symbol*, a distinguished element of N
    - If not specified otherwise, this is usually assumed to be the non-terminal on the left of the first production

Review: Derivation Relations (2)

- w A γ $\Rightarrow_{lm}$ w β γ iff A ::= β in *P*
  - derives leftmost
- α A w $\Rightarrow_{rm}$ α β w iff A ::= β in *P*
  - derives rightmost
- We will only be interested in leftmost and rightmost derivations – not random orderings

How Do We Parse with This?

- Key: given what we've already seen and the next input symbol (the lookahead), decide what to do.
- Choices:
  - Perform a reduction
  - Look ahead further
- Can reduce A=>β if both of these hold:
  - A=>β is a valid production, *and*
  - A=>β is a step in *this* rightmost derivation
- This is known as a *shift-reduce parser*

Implementing Shift-Reduce Parsers

- Key data structures
  - A stack holding the frontier of the tree
  - A string with the remaining input (tokens)
- We also need something to encode the rules that tell us what action to take next, given the state of the stack and the lookahead symbol
  - Typically a table that encodes a finite automata

Shift-Reduce Parser Operations

- *Reduce* – if the top of the stack is the right side of a handle $A ::= \beta$, pop the right side β and push the left side A
- *Shift* – push the next input symbol onto the stack
- *Accept* – announce success
- *Error* – syntax error discovered

How Do We Automate This?

- Fact: the set of viable prefixes of a CFG is a regular language(!)
- Idea: Construct a DFA to recognize viable prefixes given the stack and remaining input
  - Perform reductions when we recognize them

Encoding the DFA in a Table

- A shift-reduce parser's DFA can be encoded in two tables
  - One row for each state
  - *action* table encodes what to do given the current state and the next input symbol
  - *goto* table encodes the transitions to take after a reduction

Actions (1)

- Given the current state and input symbol, the main possible actions are
  - s_i – shift the input symbol and state *i* onto the stack (i.e., shift and move to state *i*)
  - r_j – reduce using grammar production *j*
    - The production number tells us how many <symbol, state> pairs to pop off the stack (= number of symbols on rhs of production)

Actions (2)

- Other possible *action* table entries
  - *accept*
  - blank – no transition – syntax error
    - A LR parser will detect an error as soon as possible on a left-to-right scan
    - A real compiler needs to produce an error message, recover, and continue parsing when this happens

Goto

- When a reduction is performed using A ::= β, we pop |β| <symbol, state> pairs from the stack revealing a state *uncovered_s* on the top of the stack
- goto[*uncovered_s* , *A*] is the new state to push on the stack when reducing production *A* ::= β (after popping handle β and pushing A)

LR States

- Idea is that each state encodes
  - The set of all possible productions that we could be looking at, given the current state of the parse, and
  - *Where* we are in the right hand side of each of those productions

Summary: Forms, Handles, Prefixes & Items

- If S is the start symbol of some grammar G, then:
  1. If $S =>^* \alpha$ then α is a *sentential form* of G
  2. γ is a *viable prefix* of G if there is some derivation $S =>^*_{rm} \alpha A w =>^*_{rm} \alpha\beta w$ and γ is a prefix of $\alpha\beta$.
  3. The occurrence of β in $\alpha\beta w$ is a *handle* of $\alpha\beta w$.
  4. An *item* is a marked production (a . at some position in the right hand side) [A ::= . X Y] [A ::= X . Y] [A ::= X Y .]

Problems with Grammars

- Grammars can cause problems when constructing a LR parser
  - Shift-reduce conflicts
  - Reduce-reduce conflicts

SLR Parsers

- Idea:
  1. Use information about what can follow a non-terminal to decide if we should perform a reduction
  2. Don't reduce if the next input symbol can't follow the resulting non-terminal
- We need to be able to compute FOLLOW(*A*) – the set of symbols that can follow *A* in any possible derivation
  - i.e., t is in FOLLOW(*A*) if any derivation contains *A*t
  - To compute this, we need to compute FIRST(γ) for strings γ that can follow *A*

Calculating FIRST(γ)

- Sounds easy… If $\gamma = X\ Y\ Z$, then FIRST(γ) is FIRST(X), right?
  - But what if we have the rule $X ::= \varepsilon$?
  - In that case, FIRST(γ) includes anything that can follow X, i.e. FOLLOW(X), which includes FIRST(Y) and, if Y can derive ε, FIRST(Z), and if Z can derive ε, …
  - So computing FIRST and FOLLOW involves knowing FIRST and FOLLOW for other symbols, as well as which ones can derive ε.

FIRST, FOLLOW, and nullable

- nullable(X) is true if X can derive the empty string
- Given a string γ of terminals and non-terminals, FIRST(γ) is the set of terminals that can begin any strings derived from γ
  - For SLR we only need this for single terminal or non-terminal symbols, not arbitrary strings γ
- FOLLOW(X) is the set of terminals that can immediately follow X in some derivation
- All three of these are computed together

On To LR(1)

- Many practical grammars are SLR
- LR(1) is more powerful yet
- Similar construction, but notion of an item is more complex, incorporating lookahead information

LALR(1)

- Variation of LR(1), but merge any two states that differ only in lookahead
  - Example: these two would be merged

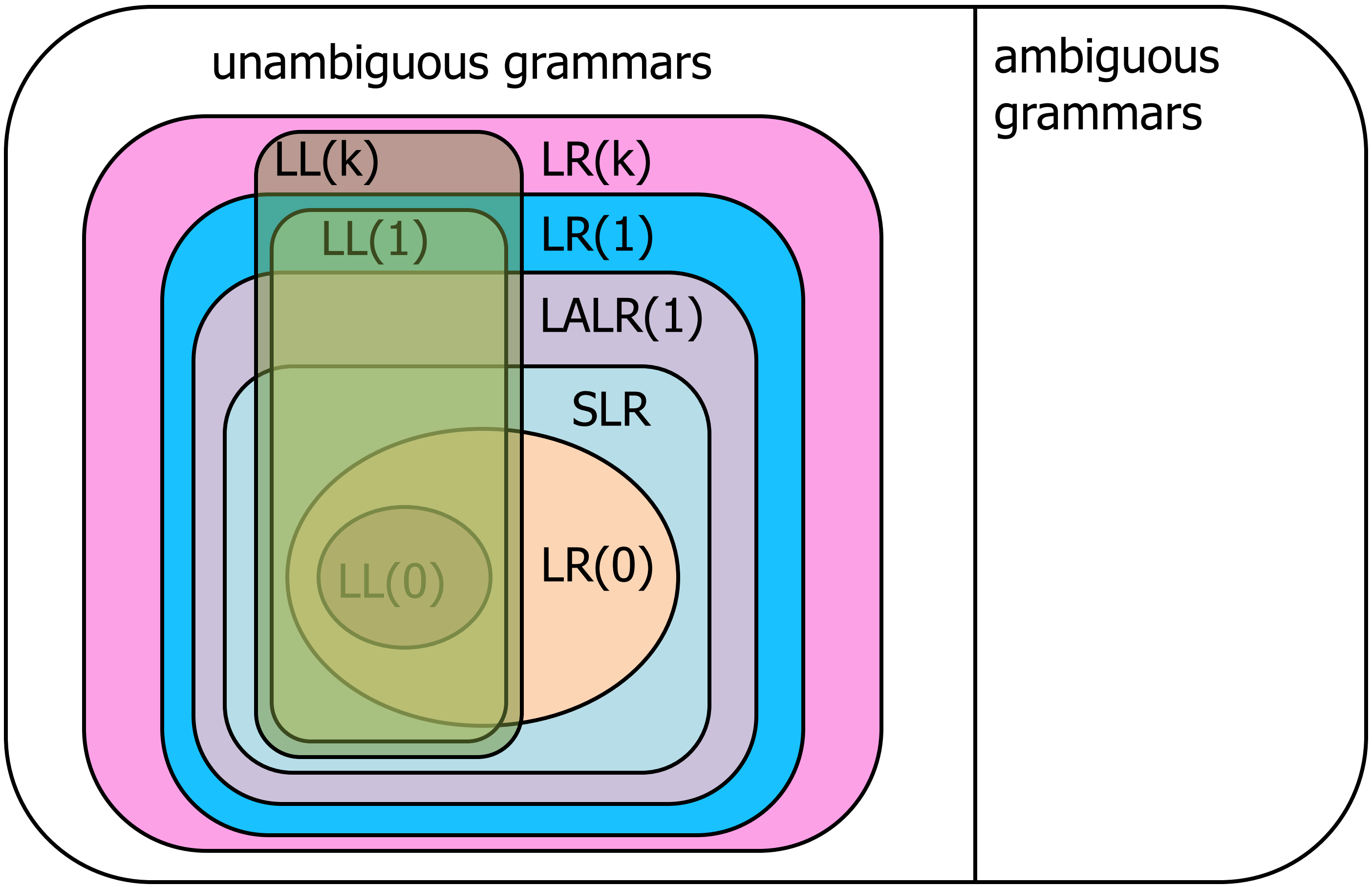
    [A ::= x . , a]

    [A ::= x . , b]

LALR(1) vs LR(1)

- LALR(1) tables can have many fewer states than LR(1)
  - Somewhat surprising result: will actually have same number of states as SLR parsers, even though LALR(1) is more powerful
  - After the merge step, acts like SLR parser with "smarter" FOLLOW sets (can be specific to particular handles)
- LALR(1) may have reduce conflicts where LR(1) would not (but in practice this doesn't happen often)
- Most practical bottom-up parser tools are LALR(1) (e.g., yacc, bison, CUP, …)

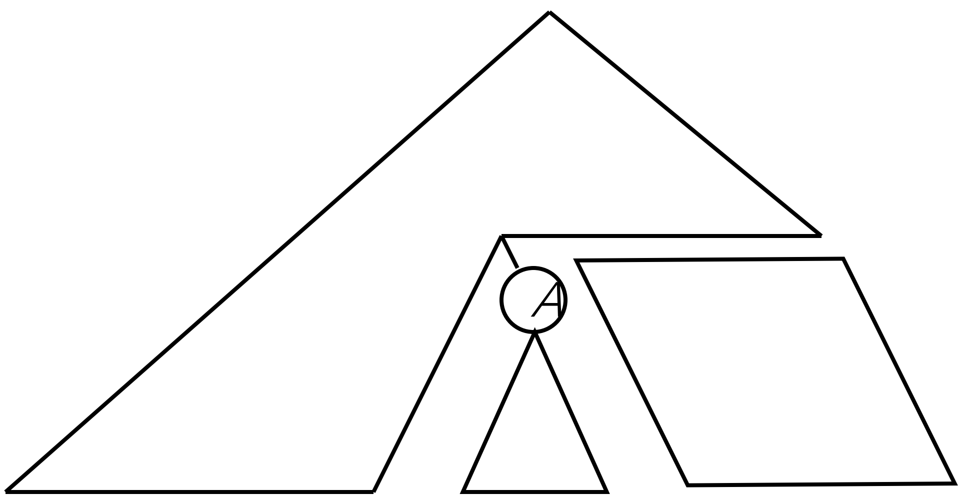
Language Hierarchies



Top-Down Parsing Strategies

Basic Parsing Strategies

- Top-Down
  - Begin at root with start symbol of grammar
  - Repeatedly pick a non-terminal and expand
  - Success when expanded tree matches input
  - LL(k)



Top-Down Parsing

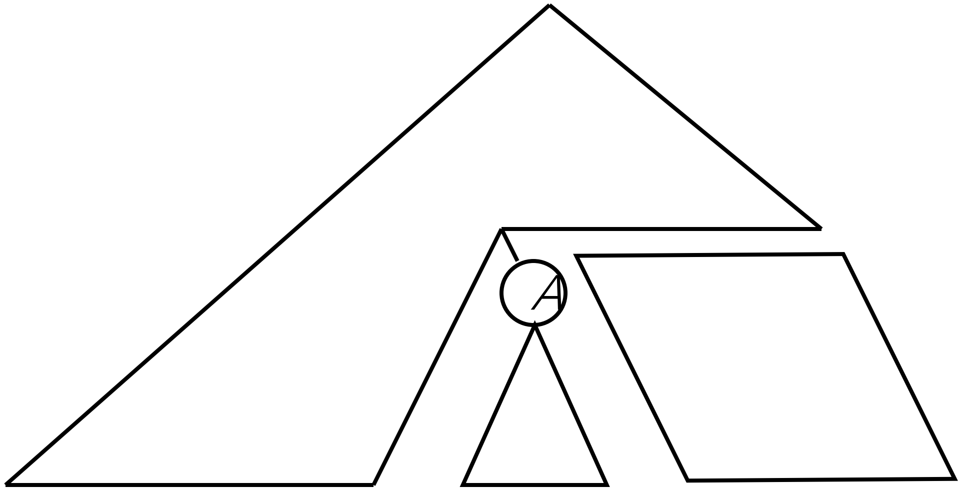
- Situation: have completed part of a left-most derivation

  $S =>^* wA\alpha =>^* wxy$

- Basic Step: Pick some production

  $A ::= \beta_1\ \beta_2\ \ldots\ \beta_n$

  that will properly expand A to match the input
  - Want this to be deterministic (i.e., no backtracking)



Predictive Parsing

- If we are located at some non-terminal *A*, and there are two or more possible productions

  $A ::= \alpha$

  $A ::= \beta$

  we want to make the correct choice by looking at just the next input symbol
- If we can do this, we can build a *predictive parser* that can perform a top-down parse without backtracking

LL(1) Property

- A grammar has the LL(1) property if, for all non-terminals A, if productions $A ::= \alpha$ and $A ::= \beta$ both appear in the grammar, then it is true that
  $\text{FIRST}(\alpha) \cap \text{FIRST}(\beta) = \varnothing$
- If a grammar has the LL(1) property, we can build a predictive parser for it that uses
  1-symbol lookahead

LL(k) Parsers

- An LL(k) parser
  - Scans the input Left to right
  - Constructs a Leftmost derivation
  - Looking ahead at most k symbols
- 1-symbol lookahead is enough for many practical programming language grammars
  - LL(k) for k > 1 is rare in practice

Table-Driven LL(k) Parsers

- As with LR(k), a table-driven parser can be constructed from the grammar
- Example
    1. S ::= (S) S
    2. S ::= [S] S
    3. S ::= ε
- Table

	(	)	[	]	$
S	1	3	2	3	3

LL vs LR (1)

- Tools can automatically generate parsers for both LL(1) and LR(1) grammars
- LL(1) has to make a decision based on a single non-terminal and the next input symbol
- LR(1) can base the decision on the entire left context (i.e., contents of the stack) as well as the next input symbol

LL vs LR (2)

∴ LR(1) is more powerful than LL(1)

- Includes a larger set of languages

∴ (editorial opinion) If you're going to use a tool-generated parser, might as well use LR

- But there are some very good LL parser tools out there (ANTLR, JavaCC, …) that might win for other reasons (documentation, IDE support, integrated AST generation, local culture/politics/economics etc.)

Recursive-Descent Parsers

- A main advantage of top-down parsing is that it is easy to implement by hand
  - And even if you use automatic tools, the code may be easier to follow and debug
- Key idea: write a function (procedure, method) corresponding to each non-terminal in the grammar
  - Each of these functions is responsible for matching its non-terminal with the next part of the input

Example: Statements

Grammar

stmt ::= *id* = *exp* ;
| return *exp* ;
| if (*exp*) *stmt*
| while (*exp*) *stmt*

Method for this grammar rule

```
// parse stmt ::= id=exp; | …
void stmt( ) {
  switch(nextToken) {
     RETURN: returnStmt(); break;
     IF:  ifStmt(); break;
     WHILE: whileStmt(); break;
     ID: assignStmt(); break;
  }
}
```

Example (more statements)

```
// parse while (exp) stmt
void whileStmt() {
    // skip "while" "("
    skipToken(WHILE);
    skipToken(LPAREN);

    // parse condition
    exp();

    // skip ")"
    skipToken(RPAREN);

    // parse stmt
    stmt();
}
```

```
// parse return exp ;
void returnStmt() {
    // skip "return"
    skipToken(RETURN);

    // parse expression
    exp();

    // skip ";"
    skipToken(SCOLON);
}
```

```
// aux method: advance past expected token
void skipToken(Token expected) {
    if (nextToken == expected)
        getNextToken();
    else error("token" + expected +
    "expected");
}
```

Recursive-Descent Recognizer

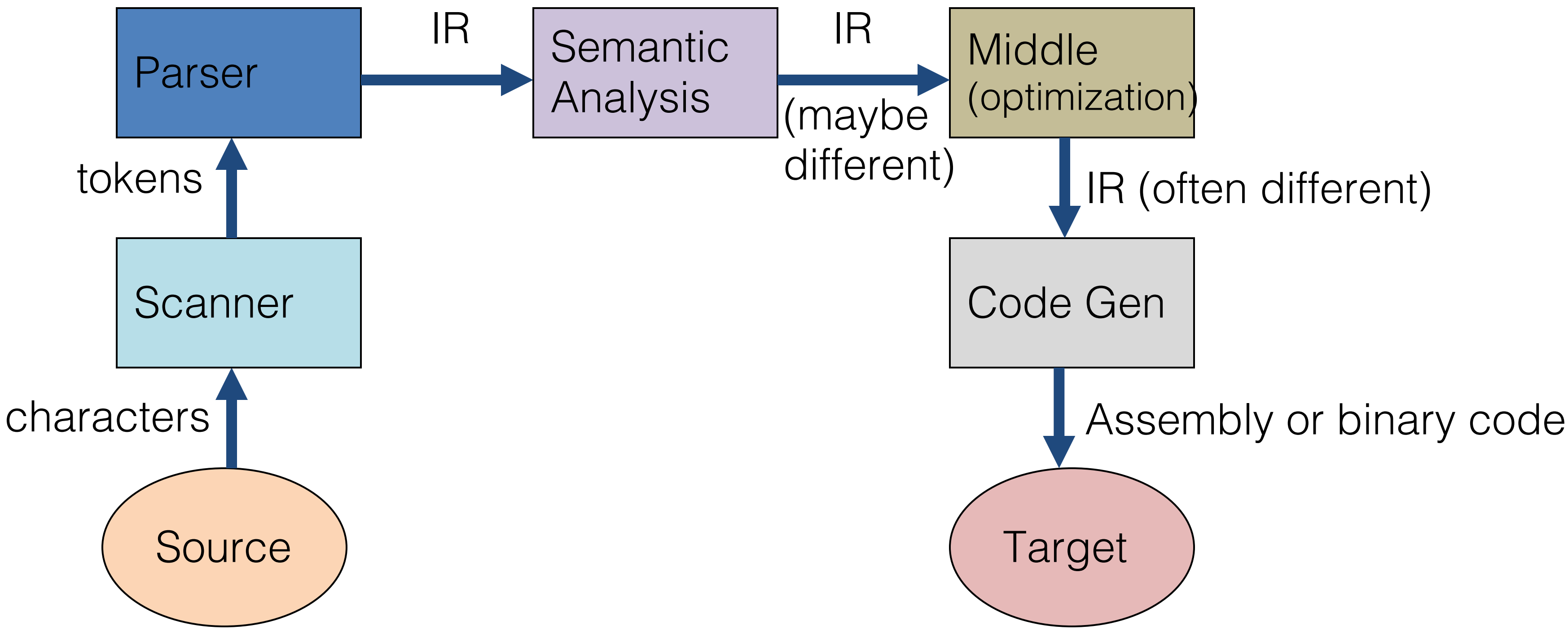
- Easy!
- Pattern of method calls traces leftmost derivation in parse tree
- Examples only handle valid programs and choke on errors.
- Real parsers need:
  - Better error recovery (don't get stuck on bad token)
  - Semantic checks (declarations, type checking, …)
  - Some sort of processing after recognizing (build AST, 1-pass code generation, …)

Invariant for Parser Functions

- The parser functions need to agree on where they are in the input
- Useful invariant: When a parser function is called, the current token (next unprocessed piece of the input) is the token that begins the expanded non-terminal being parsed
  - Corollary: when a parser function is done, it must have completely consumed input correspond to that non-terminal

Semantics

Review: Compiler Structure



What do We Need to Know to Check if This is Legal?

```
class C {
    int a;
    C(int initial) {
     a = initial;
    }
    void setA(int val) {
     a = val;
    }
}
```

```
class Main {
  public static void main(){
     C c = new C(17);
     c.setA(42);
  }
}
```

Beyond Syntax

- There is a level of correctness not captured by a context-free grammar
  - Has a variable been declared?
  - Are types consistent in an expression?
  - In the assignment x=y, is y assignable to x?
  - Does a method call have the right number and types of parameters?
  - In a selector *p.q*, is *q* a method, or field, of class instance *p*?
  - Is variable *x* guaranteed to be initialized before it is used?
  - Could *p* be null when *p.q* is executed?

What Else do We Need to Know to Generate Code?

- Where are fields allocated in an object?
- How big are objects? (i.e., how much storage needs to be allocated by new)
- Where are local variables stored when a method is called?
- Which methods are associated with an object/class?
  - How do we figure out which method to call based on the run-time type of an object?

Static Semantics

Semantic Analysis

- Main tasks:
  - Extract types and other information from the program
  - Check language rules that go beyond the context-free grammar
  - **Resolve names** – connect declarations and uses
  - **“Understand” the program** – last phase of front end …
  - … so program is “correct” for hand-off to back end
- Key data structure: Symbol tables
  - For each identifier in the program, record its attributes (kind, type, etc.)
  - Later: assign storage locations (stack frame offsets) for variables, add other annotations

Some Kinds of Semantic Information

Information	*Generated From*	*Used to process*
Symbol tables	Declarations	Expressions, statements
Type information	Declarations, expressions	Operations
Constant/variable information	Declarations, expressions	Statements, expressions
Register & memory locations	Assigned by compiler	Code generation
Values	Constants	Expressions

Semantic Checks

- Grammar = BNF
  - Short: e.g., Java in a handful of pages
- Semantics = Language Reference Manual
  - Long: Java SE 8 = 788 pages
- For each language construct, we want to know:
  - What semantic rules should be checked
  - For an expression, what is its type (is expression legal)
  - For declarations, what to capture for use elsewhere

A Sampling of Semantic Checks (0)

- Appearance of a name: id
  - **Check:** id has been declared and is in scope
  - **Compute:** Inferred type of id is its declared type
- Constant: v
  - **Compute:** Inferred type and value are explicit

A Sampling of Semantic Checks (1)

- Binary operator: exp_1 op exp_2
  - **Check:** exp_1 and exp_2 have compatible types
    - Identical, or
    - Well-defined conversion to appropriate types
  - **Compute:** Inferred type is a function of the operator and operand types

A Sampling of Semantic Checks (2)

- Assignment: $exp_1 = exp_2$
  - **Check:** exp_1 is assignable (not a constant or expression)
  - **Check:** exp_1 and exp_2 have (assignment-)compatible types
    - Identical, or
    - exp_2 can be converted to exp_1 (e.g., char to int), or
    - Type of exp_2 is a subclass of type of exp_1 (can be decided at compile time)
  - **Compute:** Inferred type is type of exp_1

A Sampling of Semantic Checks (3)

- Cast: (exp_1) exp_2
  - **Check:** exp_1 is a type
  - **Check:** exp_2 either
    - Has same type as exp_1
    - Can be converted to type exp_1 (e.g., double to int)
    - Downcast: is a superclass of exp_1 (usually requires a runtime check to verify; at compile time we can at least decide if it could be true)
    - Upcast (Trivial): is the same or a subclass of exp_1
  - **Compute:** Inferred type is exp_1

A Sampling of Semantic Checks (4)

- Field reference: exp.f
  - **Check:** exp is a reference type (not value type)
  - **Check:** The class of exp has a field named f
  - **Compute:** Inferred type is declared type of f

A Sampling of Semantic Checks (5)

- Method call: $exp.m(e_1, e_2, \ldots, e_n)$
  - **Check:** exp is a reference type (class instance)
  - **Check:** The class of exp has a method named m
  - **Check:** The method exp.m has n parameters
    - Or, if overloading allowed, at least one version of m exists with n parameters
  - **Check:** Each argument has a type that can be assigned to the associated parameter
    - Same "assignment compatible" check for assignment
    - Overloading: need to find a "best match" among available methods if more than one is compatible – or reject if result is ambiguous (e.g., C++, others)
  - **Compute:** Inferred type is given by method declaration (or could be void)

A Sampling of Semantic Checks (6)

- Return statement: return exp; or: return;
- Check:
  - If the method is not void: The expression can be assigned to a variable with the declared return type of the method – exactly the same test as for assignment statement
  - If the method is void: There is no expression

Attribute Grammars

Attribute Grammars

- A systematic way to think about semantic analysis
- Formalize properties checked and computed during semantic analysis and relate them to grammar productions in the CFG (or AST)
- Sometimes used directly, but even when not, AGs are a useful way to organize the analysis and think about it

Attribute Grammars

- Idea: associate attributes with each node in the (abstract) syntax tree
- Examples of attributes
  - Type information
  - Storage location
  - Assignable (e.g., expression vs variable – lvalue vs rvalue in C/C++ terms)
  - Value (for constant expressions)
- Notation: X.a if a is an attribute of node X

Inherited and Synthesized Attributes

Given a production $X ::= Y_1\ Y_2\ \ldots\ Y_n$

- A *synthesized* attribute X.a is a function of some combination of the attributes of the Y_i's (bottom up)
- An *inherited* attribute Y_i.b is a function of some combination of attributes X.a and other Y_j.c (top down)
  - Often restricted a bit: only Y's to the left can be used (has implications for evaluation)

Attribute Equations

- For each kind of node we give a set of equations relating attribute values of the node and its neighbors (usually children)
  – Example: $plus.val = exp_1.val + exp_2.val$
- Attribution (evaluation) means implicitly finding a solution that satisfies all of the equations in the tree
  – This is an example of a constraint language

Informal Example of Attribute Rules (1)

- Suppose we have the following grammar for a trivial language

  program ::= decl stmt

  decl ::= int id;

  stmt ::= exp = exp ;

  exp ::= id | exp + exp | 1

- What attributes would we create to check types and assignability?

Informal Example of Attribute Rules (2)

- Attributes of nodes
  - env (environment, e.g., symbol table)
    - Synthesized by decl, inherited by stmt
    - Each entry maps a name to its type and kind
  - type (expression type)
    - synthesized
  - kind (variable [var or lvalue] vs value [val or rvalue])
    - synthesized

Attributes for Declarations

decl ::= int id;

decl.env = {id ⟶ (int, var)}

Attributes for Program

program ::= decl stmt

stmt.env = decl.env

Attributes for Constants

exp ::= 1

exp.kind = val

exp.type = int

Attributes for Identifier Expressions

exp ::= id

  (type, kind) = exp.env.lookup(id)

  exp.type = type   (i.e., id type)

  exp.kind = kind   (i.e., id kind)

Attributes for Addition

$exp ::= exp_1 + exp_2$

- $exp_1.env = exp.env$
- $exp_2.env = exp.env$
- error if $exp_1.type != exp_2.type$
  - (or error if not compatible, depending on language rules)
- $exp.type = exp_1.type$ (or $exp_2.type$)
- $exp.kind = val$

Attribute Rules for Assignment

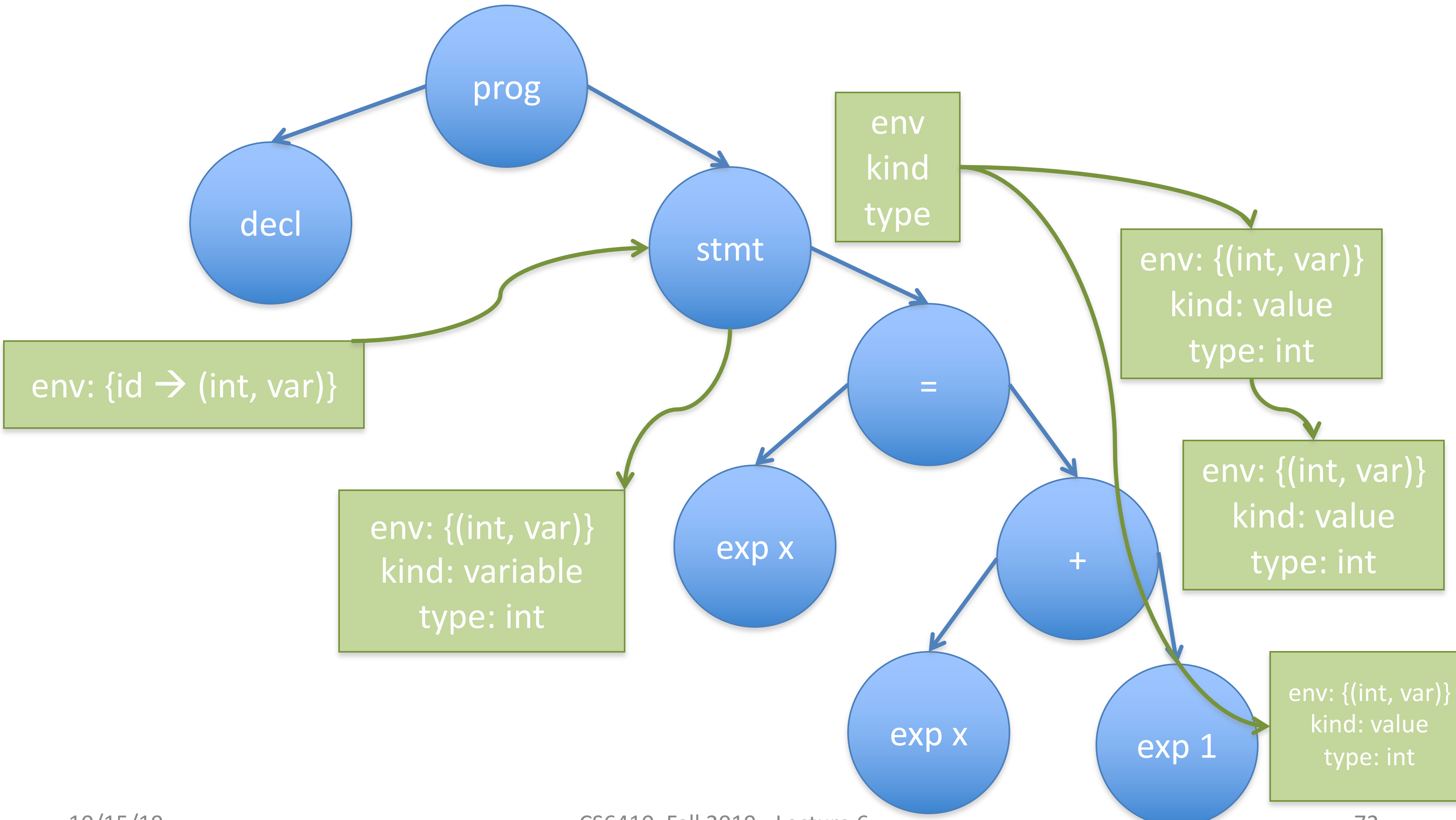
stmt ::= exp_1 = exp_2;

- exp_1.env = stmt.env
- exp_2.env = stmt.env
- Error if exp_2.type is not assignment compatible with exp_1.type
- Error if exp_1.kind is not var (can't be val)

Example

```
int x; x = x + 1;
```

Example: int x; x = x + 1;



Extensions

- This can be extended to handle sequences of declarations and statements
  – Sequences of declarations builds up larger environments
  – Each declaration synthesizes a new environment from previous one, plus the new binding
  – Full environment is passed down to statements and expressions

Observations

- These are equational computations
  - Think functional programming, no side effects
- Solver can be automated, provided the attribute equations are non-circular
- But implementation problems
  - Non-local computation
  - Can't afford to literally pass around copies of large, aggregate structures like environments

In Practice

- Attribute grammars give us a good way of thinking about how to structure semantic checks
- Symbol tables will hold environment information
- Add fields to AST nodes to refer to appropriate attributes (symbol table entries for identifiers, types for expressions, etc.)
  - Put in appropriate places in AST class inheritance tree and exploit inheritance. Most statements don’t need types, for example, but all expressions do.

Symbol Tables

Symbol Tables

- Map identifiers to
  <type, kind, location, other properties>
- Operations
  - Lookup(id) => information
  - Enter(id, information)
  - Open/close scopes
- Build & use during semantics pass
  - Build first from declarations
  - Then use to check semantic rules
- Use (and augment) in later compiler phases

Aside: Implementing Symbol Tables

- Big topic in classical (i.e., ancient) compiler courses: implementing a hashed symbol table
- These days: use the collection classes that are provided with the standard language libraries (Java, C#, C++, ML, Haskell, etc.)
  - Then tune & optimize if it really matters
    - In production compilers, it really matters
      - Up to a point…
- Java:
  - Map (HashMap) will handle most cases
  - List (ArrayList) for ordered lists (parameters, etc.)

Symbol Tables for MiniJava

- We'll outline a scheme that does what we need, but feel free to modify/adapt as needed
- Mix of global and local tables

Symbol Tables for MiniJava: Global

- Global – Per Program Information
  - Single global table to map class names to per-class symbol tables
    - Created in a pass over class definitions in AST
    - Used in remaining parts of compiler to check class types and their field/method names and extract information about them

Symbol Tables for MiniJava: Class

- One symbol table for each class
  - One entry per method/field declared in the class
    - Contents: type information, public/private, parameter types (for methods), storage locations (later), etc
- Reached from global table of class names
- In Java, we actually need multiple symbol tables (or more complex symbol table) per class
  - The same identifier can be used for both a method name and a field name in a single class

Symbol Tables for MiniJava: Global/Class

- All global tables persist throughout the compilation
  - And beyond in a real compiler…
    - Symbolic information in Java .class or MSIL files, link-time optimization information in gcc)
    - Debug information in .o and .exe files
    - Some or all information in library files (.a, .so)
    - Type information for garbage collector

Symbol Tables for MiniJava: Methods

- One local symbol table for each method
  - One entry for each local variable or parameter
    - Contents: type info, storage locations (later), etc
  - Needed for project only while compiling the method; can discard when done in a single pass compiler
    - But if type checking and code gen, etc. are done in separate passes, this table needs to persist until we're done with it
      - And beyond: often need type info for runtime debugging, memory management/garbage collection, etc
    - Even for our project, the MiniJava compiler will likely have multiple passes

Beyond MiniJava

- What we aren't dealing with: nested scopes
  - Inner classes
  - Nested scopes in methods – reuse of identifiers in parallel or inner scopes; nested functions (ML, …)
  - Lambdas and function closures
- Basic idea: new symbol table for inner scopes, linked to surrounding scope's table (i.e., stack of symbol tables, top = current innermost scope)
  - Look for identifier in inner scope; if not found look in surrounding scope (recursively)
  - Pop symbol table when we exit a scope
- Also ignoring static fields/methods, accessibility (public, protected, private), package scopes, …

Engineering Issues (1)

- In multipass compilers, inner scope symbol tables need to persist for use in later passes
  - So really can't delete symbol tables on scope exit
  - Retain and add a pointer to the parent scope (effectively a reverse tree of scope symbol tables with root = global table)
    - Keep a pointer to current innermost scope (leaf) and start looking for symbols there

Engineering Issues (2)

- In practice, want to retain O(1) lookup or something close to it
  - Would like to avoid O(depth of scope nesting), although some compilers assume this will be small enough not to matter
  - When it matters, use hash tables with additional information (linked lists of various sorts) to get the scope nesting right
    - Scope entry/exit operators

Error Recovery

- What to do when an undeclared identifier is encountered?
  - Only complain once (Why?)
  - Can forge a symbol table entry for id once you've complained so it will be found in the future
  - Assign the forged entry a type of "unknown"
  - "Unknown" is the type of all malformed expressions and is compatible with all other types
    - Allows you to only complain once! (How?)

"Predefined" Things

- Many languages have some "predefined" items (constants, functions, classes, namespaces, standard libraries, …)
- Include initialization code or declarations to manually create symbol table entries for these when the compiler starts up
  - Rest of compiler generally doesn't need to know the difference between "predeclared" items and ones found in the program
  - Can put "standard prelude" information in a file or data resource and use that to initialize
    - Tradeoffs?

Types and Type Checking

Types

- Classical roles of types in programming languages
  - Run-time safety
  - Compile-time error detection
  - Improved expressiveness (method or operator overloading, for example)
  - Provide information to optimizer
    - In strongly typed languages, allows compiler to make assumptions about possible values

Type Checking Terminology

Static vs. dynamic typing

- **Static:** checking done prior to execution (e.g. compile-time)
- **Dynamic:** checking during execution

Strong vs. weak typing

- **Strong:** guarantees no illegal operations performed
- **Weak:** can't make guarantees

Caveats:

- Hybrids common
- Inconsistent usage common
- "untyped," "typeless" could mean dynamic or weak

	static	dynamic
strong	Java, SML	Scheme, Ruby
weak	C	PERL

Type Systems

- Base Types
  - Fundamental, atomic types
  - Typical examples: int, double, char, bool
- Compound/Constructed Types
  - Built up from other types (recursively)
  - Constructors include records/structs/classes, arrays, pointers, enumerations, functions, modules, …
    - Most language provide a small collection of these

How to Represent Types in a Compiler?

Create a shallow class hierarchy

- Example:

```
   abstract class Type { … }    // or
interface
   class BaseType extends Type { … }
   class ClassType extends Type { … }
```

- Should not need too many of these

Types vs ASTs

- Types nodes are not AST nodes!
- AST = abstract representation of source program (including source program type info)
- Types = abstract representation of type semantics for type checking, inference, etc.
  - Can include information not explicitly represented in the source code, or may describe types in ways more convenient for processing
- Be sure you have a separate "type" class hierarchy in your compiler distinct from the AST

Base Types

- For each base type create exactly one object to represent it (singleton pattern!)
  - Symbol table entries and AST nodes reference these objects to represent entry/node types
  - Usually created at compiler startup
- Useful to create a type "void" object to tag functions that do not return a value
- Also useful to create a type "unknown" object for errors
  - ("void" and "unknown" types reduce the need for special case code in various places in the type checker; don't have to return "null" for "no type" or "not declared" cases)

Compound Types

- Basic idea: use a appropriate "type constructor" object that refers to the component types
  - Limited number of these – correspond directly to type constructors in the language (pointer, array, record/struct/class, function)
  - So a compound type is represented as a graph
- Some examples…

Class Types

- Type for: class Id { fields and methods }

```
class ClassType extends Type {
   Type baseClassType;      // ref to base class
   Map fields;              // type info for
fields
   Map methods;             // type info for
methods
}
```

(MiniJava note: May not want to represent class types exactly like this, depending on how class symbol tables are represented; e.g., the class symbol table(s) might be a sufficient representation of a class type.)

Array Types

- For regular Java this is simple: only possibility is # of dimensions and element type (which can be another array type or anything else)

```
class ArrayType extends Type {
   int nDims;
   Type elementType;
}
```

Methods/Functions

- Type of a method is its result type, plus an ordered list of parameter types

```
class MethodType extends Type {
    Type resultType;        // type or
"void"
    List parameterTypes;
}
```

- Sometimes called the method "signature"

Type Equivalance

- For base types this is simple: types are the same if they are identical
    - Can use pointer comparison in the type checker if you have a singleton object for each base type
  - Normally there are well defined rules for coercions between arithmetic types
    - Compiler inserts these automatically where required by the language spec or when written explicitly by programmer (casts) – often involves inserting cast or conversion nodes in AST

Type Equivalence for Compound Types

- Two basic strategies
  - *Structural equivalence*: two types are the same if they are the same kind of type and their component types are equivalent, recursively
  - *Name equivalence*: two types are the same only if they have the same name, even if their structures match
- Different language design philosophies
  - e.g., are Complex and Point the same?
  - e.g., are Point (Cartesian) and Point (Polar) the same?

Structural Equivalence

- Structural equivalence says two types are equal iff they have same structure
  - Atomic types are tautologically the same structure and equal if they are the same type
  - For type constructors: equal if the same constructor and, recursively, type (constructor) components are equal
- Ex: atomic types, array types, ML record types
- Implement with recursive implementation of equals, or by canonicalization of types when types created, then use pointer/ref. equality

Name Equivalence

- Name equivalence says that two types are equal iff they came from the same textual occurrence of a type constructor
  - Ex: class types, C struct types (struct tag name), datatypes in ML
  - special case: type synonyms (e.g. typedef in C) do not define new types
- Implement with pointer equality assuming appropriate representation of type info

Type Equivalence and Inheritance

- Suppose we have

```
class Base { … }
class Derived extends Base { … }
```

- A variable declared with type Base has a *compile-time type* or *static type* of Base
- During execution, that variable may refer to an object of class Base or any of its subclasses like Derived (or can be null), often called the the *runtime type* or *dynamic type*
  - Since subclass is guaranteed to have all fields/methods of base class, type checker only needs to deal with declared compile-time types of variables and, in fact, can't track all possible runtime types

Type Casts

- In most languages, one can explicitly cast an object of one type to another
  - Sometimes cast means a conversion (e.g., casts between numeric types)
  - Sometimes cast means a change of static type without doing any computation (casts between pointer types or pointer and numeric types in C)
  - For objects can be a upcast (free and always safe) or downcast (requires runtime check to be safe)

Type Conversions and Coercions

- In full Java, we can explicitly convert a value of type double to one of type int
  - can represent as unary operator
  - typecheck, codegen normally
- In full Java, can implicitly coerce an value of type int to one of type double
  - compiler must insert unary conversion operators, based on result of type checking

C and Java: type casts

- In C/C++: safety/correctness of casts not checked
  - Allows writing low-level code that's type-unsafe
  - C++ has more elaborate casts, and at least one of them does imply runtime checks
- In Java: downcasts from superclass to subclass need runtime check to preserve type safety
    - static typechecker allows the cast
    - codegen introduces runtime check
      - (same code needed to handle "instanceof")
    - Java's main need for dynamic type checking

Various Notions of Type Compatibility

- There are usually several relations on types that we need to analyze in a compiler:
  - "is the same as"
  - "is assignable to"
  - "is same or a subclass of"
  - "is convertible to"
- Exact meanings and checks needed depend on the language specifications
- Be sure to check for the right one(s)

Useful Compiler Functions

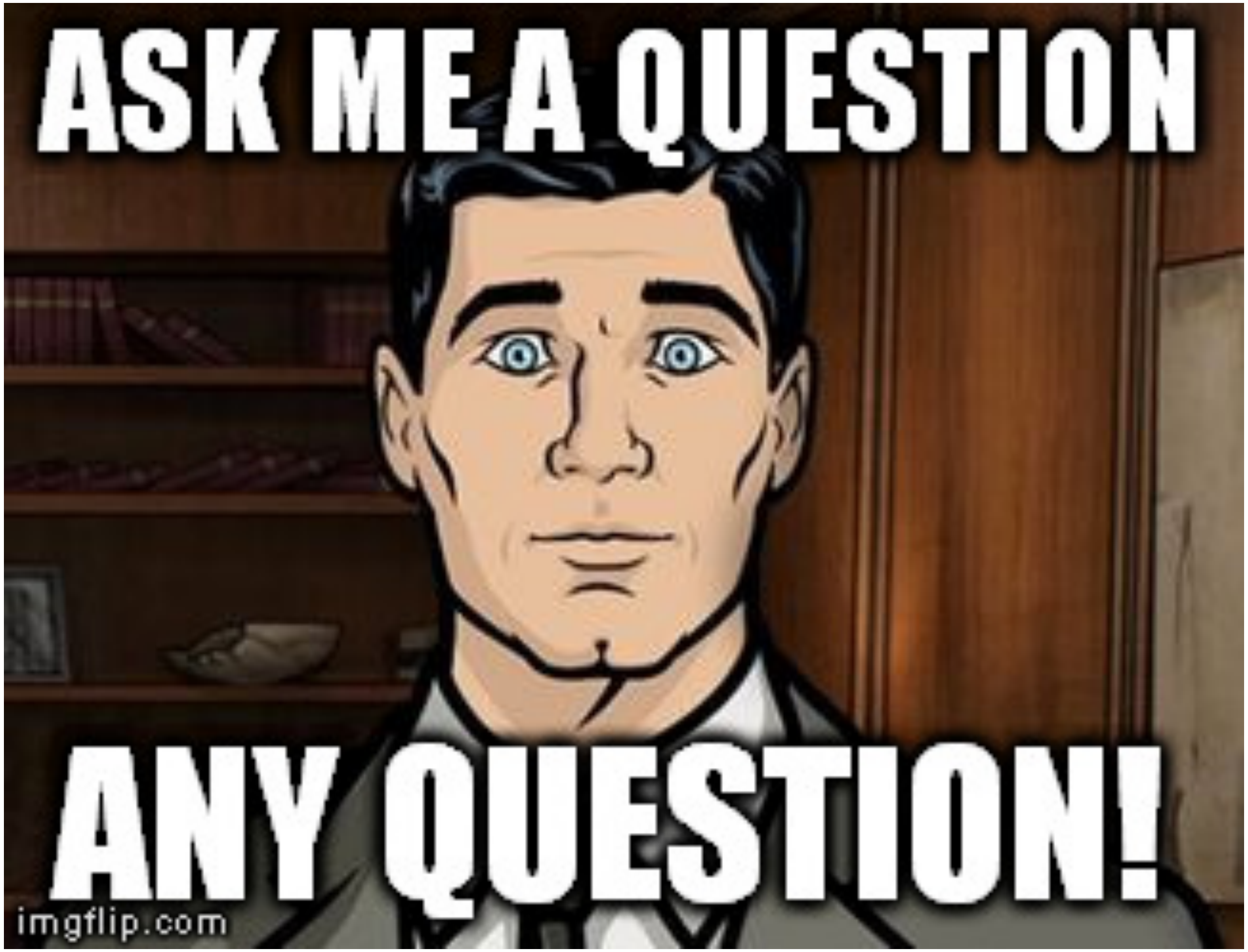
- Create a handful of methods to decide different kinds of type compatibility:
  - Types are identical
  - Type t_1 is assignment compatible with t_2
  - Parameter list is compatible with types of expressions in the method call
- Usual modularity reasons: isolates these decisions in one place and hides the actual type representation from the rest of the compiler
- Probably belongs in the same package with the type representation classes

Implementing Type Checking for MiniJava

- Create multiple visitors for the AST
- First pass/passes: gather information
  - Collect global type information for classes
  - Could do this in one pass, or might want to do one pass to collect class information, then a second one to collect per-class information about fields, methods – you decide
- Next set of passes: go through method bodies to check types, other semantic constraints

Coming Attractions

- To get a running compiler we need:
  - Execution model for language constructs
  - x86-64 assembly language for compiler writers
  - Code generation and runtime bootstrap details
- We'll also spend considerable time on compiler optimization
  - Intermediate reps., graphs, SSA, dataflow
  - Optimization analysis and transformations
- Immediate problem is to keep lectures from getting too far ahead of the project - maybe hold off on runtime details?
  - Thoughts? Suggestions? Opinions?



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